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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A natural gas leak from a poly(vinyl chloride) (PVC) gas transmission line was the reported cause of a fatal explosion in a motel complex in Las Vegas, Nevada. An analysis of the pipe was conducted to determine the cause of failure. The results indicated that the pipe compound had not been properly fused during the extrusion process. In connecting the plastic pipe to a metal pipe, a solvent-based primer had been used to activate the adhesive on a pipe wrap tape, applied over the plastic pipe and a compression fitting. The solvent apparently caused gross swelling of the pipe, beneath the tape, negating the effect of a metal insert stiffener. Subsequent creep deformation of an adjacent section of the plastic pipe apparently exerted sufficient tensile stress on the swollen portion of the plastic pipe to induce the formation of a stress crack.

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Failure analysis; Gas pipe; Natural gas pipe; Plastic gas pipe; Poly(vinyl chloride) gas pipe

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Failure Analysis of a Polyethylene (PE) Natural Gas Service Line from Bowie, Maryland (NBS Failure Analysis No. 107)

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May 1974

This is a final report.

Prepared for
Pipeline Safety Division
National Transportation Safety Board
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FAILURE ANALYSIS OF A POLYETHYLENE (PE) NATURAL GAS SERVICE LINE FROM BOWIE, MARYLAND (NBS Failure Analysis No. 107)

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

A section of polyethylene plastic pipe from a natural gas service line was received for evaluation of the cause of an in-service failure. This failure analysis was conducted at the request of, and under the sponsorship of, the Pipeline Safety Division, National Transportation Safety Board. Immediately prior to receipt of the pipe, it had been in the possession of the Office of the Fire Marshall, Prince Georges County, Maryland. The pipe contained a single crack in the wall. It was reported to us that gas leakage from this crack was the substantive cause of a fatal explosion and fire on June 23, 1973, in a private residence served by the line, located at 12321 Welling Lane, Bowie, Maryland.

The damaged section of pipe was obtained at a meeting held in this laboratory, attended by several persons, the purpose of which was to discuss the possible approaches to the conducting of a failure analysis. Among those present were a representative of the manufacturer of the basic plastic resin, and a representative of the resin manufacturer's subsidiary which fabricated the pipe. These individuals provided the following information:

1. The basic pipe compound consisted of a carbon-black filled polyethylene-1-butene copolymer.

2. The pipe compound contained a tracer compound, consisting of a metal oxide, used exclusively by the manufacturer as a means of identifying its materials, in which the metal content was nominally 5 ppm.

3. Copies of the specifications for both the pipe compound and the fabricated pipe, which were in effect at the time of manufacture of this particular pipe, which was estimated to have been in the latter part of 1965, were provided. These specifications included data on the properties of the pipe compound, as well as dimensions, tolerances, pressure ratings and similar data on the fabricated pipe, including recommended installation procedures. Although the pipe was not so marked, the technical brochures indicated that it was in compliance with Commercial Standards CS197-60 and CS255-63, and was in compliance with type PE3306 plastic pipe as described in the latter standard. This code indicates that the pipe compound was produced from Type 3, Grade 3, high density polyethylene resin and had a hydrostatic design stress rating of 600 psi for water at 23°C (73.4°F).

4. This particular pipe was pressure rated for continuous use at pressures up to 190 psi for water and 95 psi with natural gas at 23°C (73.4°F).

A representative of the gas company, also present at the meeting, provided the following:

1. The pipe had been purchased by the gas company and then given to a contractor, who installed the service line in December 1965. The final connection of the service line to the main had been conducted by gas company personnel. The service line had been installed at a depth of 102 cm (40 in) below ground level, and in the process of coupling it to the steel main, had been bent upward at an angle of approximately 30 degrees and attached to a tee on the main by means of a standard compression fitting.

2. The nominal working pressure in the service line was about 20 psig.

3. In the months subsequent to the installation, a paved street and sidewalks had been installed in such a location that the steel main was beneath the sidewalk on the opposite side of the street from that on which the house in question was located.

4. The crack in the service line was located approximately 46 cm (18 in) from the line-to-main coupling.

5. An additional 1.86 m (6 ft) long section from the same continuous length of pipe as that containing the crack was submitted for use as needed in the test program. This section had been exhumed from the service line trench at a site across the street from the cracked section, and had been pressure tested for leaks following the explosion.

In addition to the above information, a request was also made to attempt to determine the approximate volume leakage rate, using air, rather than natural gas, while the cracked section was subjected to a pressure of about 20 psig.

Preliminary Examination of the Pipe

The damaged section of pipe was about 46 cm (1.5 ft) in length, with the crack located at approximately the mid-point of the length of the exhumed section. Identifying marks on the pipe included the producer's tradename and the pipe size, i.e. Schedule 40, 1/2-inch. The section of pipe was permanently bowed as illustrated in Figure 1. The crack was approximately 3.8 cm (1.5 in) long and in a modified "J" shape, with the stem of the "J" extending in the longitudinal direction of the pipe, as illustrated in Figure 2. The longitudinal portion was on the order of 2 cm (0.8 in) in length, with the remaining curved portion extending about an additional 0.5 cm (0.2 in) in the longitudinal direction. The curved portion of the crack extended to a point where it

was about 45 degrees to the transverse and longitudinal axes. The longitudinal section of the crack was located essentially on the inside of the bow.

The pipe was visibly flattened at a point just beyond the end of the longitudinal portion of the crack. At the point where the longitudinal portion began to curve, microscopic examination revealed the presence of a slight gap in the outer surface of the pipe. Preliminary tests, using 10 psig of nitrogen pressure, indicated that this part of the crack seemed to have the highest leakage rate. This portion of the crack, measuring about 0.5 cm (0.2 in) in length, was the only part of the crack in which there was an obvious separation of the two crack surfaces in the outer surface of the pipe. Unfortunately, there was no way of determining whether this gap was present prior to exhumation of the section, or whether it occurred as a result of intentional attempts to straighten the section, e.g., to visually attempt to examine the interior of the pipe, by any of the several persons known to have had access to the pipe prior to its acceptance in this laboratory. This particular section of the crack, because of its location on the inside of the permanent bow in the pipe, would most probably have been subjected to more tensile stress than any other part of the crack if the pipe were manually straightened. Consequently, the flow rates, subsequently measured and reported in another section of this report, are probably higher than those which would have occurred while the pipe was still in service.

Following this preliminary work, the cracked section of pipe, still in its "as received" condition was submitted to the NBS Fluid Meters Section, Mechanics Division, for the air leakage tests. The pipe was pressurized to approximately 20 psig (34-35 psia) and maintained at that pressure for 30 minutes. The results are given in Table 1. The slight increase in flow rate observed after 30 minutes of test was attributed to a possible slight straightening of the pipe.

Materials Tests

All of the following tests were conducted from specimens taken from the 1.86 meter (6 foot) section of pipe.

The pipe compound was subjected to an infrared spectrographic analysis, and subsequently qualitatively identified as a polyethylene-1-butene copolymer.

The presence of the metallic oxide tracer was established by means of neutron activation analysis, and quantitatively verified as being present in approximately the specified amount of 5 ppm, reported as the metal. These tests were performed by a member of the staff of the NBS Activation Analysis Section, Analytical Chemistry Division. When the sample was analyzed in triplicate the metal content was found to be 4.1, 4.6, and 18 ppm. Since the abnormally high value of the one sample was

believed to be due to inhomogeneity of the oxide in the pipe compound, or due to accidental contamination of the sample during preparation, a fourth analysis was conducted and the metal content found to be 4.1 ppm.

The density measurements on specimens of the pipe were obtained using the procedures described in the American Society for Testing and Materials (ASTM) Method D1505-68, Standard Method of Test for Density of Plastics by the Density Gradient Technique. The average density was found to be 0.9545 gm/cm^3, within the range expected for the specified nominal density of 0.960 gm/cm^3 for the basic pipe compound.

The melt index (M.I.) of the pipe was determined using the procedures described in the ASTM Method D1238-70, Standard Method of Measuring Flow Rates of Thermoplastics by Extrusion Plastometer. The measured M.I. Value of 0.28 was within the range expected for the specified nominal value of 0.30.

Flattening tests were conducted on specimens of pipe. The flattening test is a standard test procedure for most plastic pipe, although it is not an applicable test for new polyethylene pipe. In this analysis it was used simply to determine possible embrittlement of the pipe compound. These tests normally consist of placing a specimen between parallel plates, and applying a compressive force over a period of 2 to 5 minutes, until the specimen is flattened to 40% of its original actual measured outside diameter. In this case, however, the pipe was completely crushed until the inner walls were in intimate contact. This required an applied force of approximately 45 kg/cm (250 lb/in) of length of the pipe specimen. Neither of two specimens tested showed any evidence of splitting, crazing, or cracking that might indicate deterioration of the pipe. One additional specimen was first prepared by putting a longitudinal cut, using a surgical scapel, about 0.6 cm (0.25 in) in length along the inner wall. The nicked section was aligned with the upper plate and the flattening test repeated, but the crushing force was maintained for 5 seconds after the inner walls had made contact. This test was strictly an arbitrary one intended to induce stress cracking. It was felt that any significant extention of the crack might be indicative of poor molding techniques or deterioration due to aging. No evidence of either were noted when the specimen was cross-sectioned for the purpose of microscopically examining the cut.

The density and M.I. values, as well as the absence of cracking or splitting of the pipe or lengthening of the nick in the flattening tests, were considered to be relatively good indications that there had been no apparent deterioration of the pipe compound due to poor extruding or fabricating techniques or subsequent aging.

<u>Dimensional Measurements</u>

Three specimens, cut from the 1.86 meter section of pipe, were measured to determine compliance with the manufacturer's specifications with respect to the outside diameter and the wall thickness. The

average O.D., based on the minimum and maximum measured values, met the requirements. All three specimens met the maximum, but two were slightly below the minimum wall thickness requirements. However, in the latter case, the standard micrometer normally recommended for measuring pipe wall thickness was unavailable, and a modified micrometer of slightly less accuracy was used. In view of this, and considering the low working pressure in the pipe, this minor variation was not considered to have a significant bearing on the strength of the pipe. Later when the crack was opened, wall thickness measurements along the edges of the crack, particularly in the immediate area of the probable point of initiation of the crack, indicated that the wall thickness was within compliance, with respect to the manufacturer's specification.

The cracked section of the pipe contained a visibly flattened area just beyond the end of the longitudinal portion of the crack. Consequently, an O.D. profile was made of the pipe over a 30.5 cm (12 in) length. Starting at a point on the longitudinal section of the crack, located approximately 1.5 cm (0.6 in) from the end of the longitudinal portion and about 0.25 to 0.50 cm (0.1 to 0.2 in) from where the crack began to curve, the pipe was marked off in 1.27 cm (0.5 in) increments for a distance of 15 cm (6 in) in each direction from this central point. A diameter of the pipe (intersecting the crack) in a transverse plane passing through the midpoint of the crack was arbitrarily considered to be at 0°. In this plane, and in parallel planes at 1.27 cm (0.5 in) increments, the diameter of the pipe was measured at approximately 45, 90, and 135°, considering the 0° point to be in the same circumferential position in each plane. Of all of these measurements only three 0° measurements, located at 1.27-, 2.54-, and 3.8-cm (0.5-, 1.0-, and 1.5-in) from the central point, in the direction away from the curved portion of the crack failed to meet minimum O.D. requirement, with the flattest point at the 2.54-cm (1.0-in) location. At each of these three locations the 90° measurement exceeded the maximum O.D. requirement.

Visual and Microscopic Examination of the Crack

A 13-cm (5-in) long section of the pipe containing the crack was removed by making transverse cuts about 5 cm (2 in) beyond each end of the crack. This section was then cut open in the longitudinal direction to expose the inner wall. Two items were immediately observed: 1) the crack extended for an additional 3.2 cm (1.25 in) in the longitudinal direction along the inner wall, although not in as straight a line as that on the outer pipe surface; and 2) most importantly, an occluded particle was observed embedded in the crack and protruding through the inner wall surface. The particle was located approximately 0.5 cm (0.2 in) from the end of the curved portion of the crack. The protruding part of the particle was sharp to the touch and appeared to be firmly embedded in the crack. Under microscopic examination the particle appeared to be a grain of sand. In addition, it was noted that some of the plastic had been extruded downward, that is, into the interior of the pipe, around the particle on both sides of the crack. The distortion

of the inner wall surface caused by the displaced plastic material appeared to be somewhat greater along the inner side of the curvature of the crack. The occluded particle is shown in Figure 3.

The crack was then opened by making transverse cuts to points as closely as possible to the ends of the crack as it appeared on the outer surface of the pipe. When the second cut was completed the two pieces separated readily, and although the occluded particle fell out at this time, it was recovered. It should be noted that this situation had been considered prior to the opening of the crack and, consequently, the exact location of the particle had been marked on the inner surface of the pipe.

Subsequently, the two surfaces of the crack were carefully examined by means of a stereo microscope over an approximate range of 12X to 60X magnification. The most significant points of interest were those areas including and surrounding the location of the occluded particle. At the point where the particle was located, each crack surface contained a discrete cavity. The one on the crack surface along the inner part of the curvature appeared to be slightly deeper than that on the opposite surface. However, each cavity seems to have rather discrete characteristics which would indicate, at the first approximation, that the particle had become occluded while the pipe compound was still soft, i.e., during the initial extrusion of the pipe. One of the recommended procedures in the extrusion of this type of polyethylene pipe compound was that a 20/80/20 - mesh breaker screen pack be used in the extruder. Assuming this technique was used, the particle, if it had been a contaminant in the original pipe compound, would not have passed through an undamaged 80 - mesh screen, although it was small enough to pass through a 20 mesh screen. However, this does not preclude the possibility of accidental contamination of the screen pack or extruder on the downstream side of the 80 - mesh screen. The inner wall of the pipe directly opposite the particle was carefully examined on the assumption that if the particle had gotten into the pipe during the installation, and was subsequently crushed with sufficient force to embed the particle into the pipe wall, that there should have been some visible damage on the opposite wall. No such damage was evident under microscopic examination. In addition, when a section of pipe was crushed, in a laboratory test, until the inner surfaces were in intimate contact, the specimen was permanently distorted out-of-round with respect to the specification requirements, a condition not observed in the immediate area of the occluded particle.

The sides of the crack above the particle extending to the outer pipe surface were examined for abrasion marks, such as could be expected to have been caused by the particle being forced into the crack from the outside. No such damage was observed. However, if such a situation had occurred, this would mean that the crack was already present when the particle was forced for fell into the crack. Since the site of the occluded particle was believed to be the obvious point of initiation of the stress crack, it would appear to have been too fortuitous for the stress crack to have been present and that the particle just happened to

fall into and become lodged at this exact point. In addition, when the sample was received there was no visible gap in the outer surface of the pipe wall through which the particle could have fallen. This portion of the crack was towards the inside of the bow in the pipe, and presumably could have been held closed by slight compressive forces at or near the outer surface of the pipe.

Above and around the particle cavity, the surfaces exhibited evidence of a brittle fracture of the type typically associated with stress cracking. One surface, in particular, was evenly coated with a rust-like stain, approximately 0.75 cm (0.3 in) in width, surrounding the particle cavity and extending to the outer surface of the pipe wall. The opposing surface also exhibited staining, although not as evenly distributed over the entire surface, but also extending to the outer surface. As a result of these observations it was concluded that the occluded particle created a stress point which later resulted in the formation of a stress crack extending through the pipe wall at that location. This crack presumably, because of the observed stains, occurred and resulted in the initial gas leak, at some extended period of time prior to the development of the crack to the size observed in the exhumed pipe. There was one other place in the crack, approximately 0.25 cm (0.1 in) in width, located at approximately the outer end of the longitudinal portion of the crack, as observed on the outer surface, where similar rust-like stains covered both surfaces of the crack from the inner to the outer surface. However, the density of the color of these stains subjectively appeared less than those surrounding the occluded particle. This site appeared to have been the possible origin of a second gas leak. One possible assumption of its occurrence is that the crack propagated along the inner wall of the pipe, from the site of the occluded particle, and that a rupture at this point could have resulted from stresses in the pipe wall, since this site was located just within the area where the pipe began to be flattened out-of-round. Although the pipe wall was completely cracked through between the particle and the other site of stains, there were no stains that extended to the outer surface, although some staining of the sides of the crack were observed near the inner surface. This seemed to indicate that this portion of the crack, at least near the outer surface, was relatively recent. There were other random rust-like stains on the inner wall of the pipe, which indicated that their source, as well as those in the crack, could have been the nearby steel main.

Two other potential sources of stress were noted as a result of the visual examinations. The flattened portion of the pipe, noted above, was in the area where the inner wall was cracked. The outer wall contained a group of pits with embedded dirt and sand as though someone had stepped on the pipe. However, after noting comparable abrasions at various points around the circumference of the long section, where the pipe was not out-of-round, it was surmised that they may have been due to soil compaction, expansion and contraction or the like and that the flattening may have been due to straightening of the pipe. This assumes

that the pipe was firmly held by the nearby compression fitting, and that flattening was not a fabrication defect. Such straightening could have produced tensile stresses near the outer surface in the cracked area. There was also the possibility that the flattened area was due to kinking of the pipe at some point in time prior to, or during, installation, a situation which could result in permanent out-of-roundness. The other observation was that both sections of pipe contained a pair of shallow, parallel grooves along the inner surface that were probably caused by the extruder die. Although both sections were bowed, these grooves were out of phase by about 90° with respect to their location and the direction of bowing. One of the grooves was immediately adjacent to the occluded particle on the side towards the curved portion of the crack, and the other somewhat closer to the curve, and both were located essentially along the inside of the bow in this section of pipe. The two grooves in the long section were located along the side of the inner wall with respect to the bow. This indicated that the pipe may have been twisted during installation, since the pipe is normally snaked back and forth along the bottom of the trench. If twisting occurred as a result of installation, then residual torsional stresses could also have been present in the crack area. Stresses due to either or both of these possibilities would be expected to decrease the resistance of the plastic to stress cracking.

Conclusions

From this investigation, it was concluded that the cause of failure appeared to be due to a stress crack initiated by the presence of an occluded particle, which acted as a stress point, in the inner wall of the pipe. All observations seemed to indicate that the particle became lodged in the wall during some stage of its fabrication, and that in acting as a stress point, weakened the pipe. The stress crack probably propagated to its final size as a result of exposure to a variety of possible forces on, and possibly within, the pipe wall.

Evidence obtained by microscopic examination indicated the occurrence of a small leak through the pipe wall at a point directly above the site of the occluded particle, and a second probable small leak that appeared to have been caused in part by the presence of the stress crack which had propagated along the inner wall from the site of the occluded particle. The full crack between, and extending slightly beyond these two sites, may have been very recent; and as far as final propagation through the outer surface in the pipe wall was concerned, may have been abrupt in nature.

Table 1. Results of Air Leakage Tests

Time	P	T	Air Leak Rate	
	psia	°F	CFM at P, T a/	CFM at 14.7 psia, 70°F b/
Start	34.0	71.2	2.31	5.32
	35.1	71.2	2.55	6.08
1/2 hr. later	35.1	70.5	2.86	6.80
	34.0	70.5	2.82	6.50

a/ CFM ($ft^3 min^{-1}$) at conditions inside the tube of pressure, P, and temperature, T.

b/ Same leak at the same test conditions expressed as a volume rate of air at 14.7 psia and 70°F.

Figure 1. Cracked section of pipe "as received", arrows indicate location of the crack.

Figure 2. Close-up of crack with arrows showing extent of crack on the outer surface of the pipe.